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Localization length determination for the two-dimensional electrons in the δ-doped GaAs/AlGaAs heterostructures from acoustical studies of the quantum Hall regime

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Introduction

In the disordered two-dimensional systems at low temperatures (quantum Hall effect regime) the electrons are localized and the conductivity is of a hopping type. The electronic wavefunction in this case is characterized by a single dimension: the localization length. The localization length is usually obtained from dc conductivity measurements when the variable-length hopping conductivity takes place. In the case of the integer Hall effect (for the magnetic fields corresponding to the middle of the Hall's plateau) the static (dc) conductivity is zero. The high-frequency hopping conductivity manifests itself in this case and it is due to the electronic transitions between the localized states with close energies situated in the vicinity of the Fermi level. The states effective for such transitions form compact pairs, rather distant from each other. There are no transitions between these pairs, that is why there is no current in a static field. However, the high-frequency electric field producing transitions within the pairs, polarizes them, thus the high-frequency conductivity appears to be non-zero. As it has been pointed out by Efros [1], the high-frequency hopping conductivity of the two-dimensional electrons is a complex quantity $\sigma_{xx} = \sigma_1 - i\sigma_2$ and $\sigma_2 > \sigma_1, \sigma_1 \propto \xi$, where ξ is the localization length.

Hence, the study of hf-conductivity provides one more method to determine the localization length and which is important, in a magnetic field when the dc-conductivity is zero. Acoustical methods have proved to by very effective for the study of the hf-hopping conductivity. One measures the attenuation Γ and the relative velocity change $\Delta V/V$ of a surface acoustic wave (SAW) both attributable to the SAW interaction with the two-dimensional electrons of a heterostructure. The detailed account of the acoustical method is given elsewhere [2]. The simultaneous measurement of Γ and $\Delta V/V$ makes it possible to determine σ_1 and σ_2 without any need of electric contacts.

Experimental results and discussion

In [3, 4] Γ and $\Delta V/V$ have been measured for a SAW at 30 MHz in GaAs/AlGaAs heterostructures with $n = (1.3–2.8) \times 10^{11}$ — in a temperature range of 1.5–4.2 K and in a magnetic field up to 7 T. Figure 1(a) shows the σ_1 and σ_2 magnetic field dependencies at $T = 1.5$ K. σ_1 and σ_2 have been calculated from Γ and $\Delta V/V$ using the relations of [3, 4]. The σ_1 and σ_2 dependencies on ν, the filling factor, for different temperatures and at ν near to $\nu = 2$ are presented in Fig. 1(b) ($H = 5.5$ T, $\nu = nch/eH$, $c = 3 \times 10^{10}$ cm/s, $h = 6.62 \times 10^{-27}$erg · s, $e = 4.8 \times 10^{-10}$ CGS). One can see from this figure that for

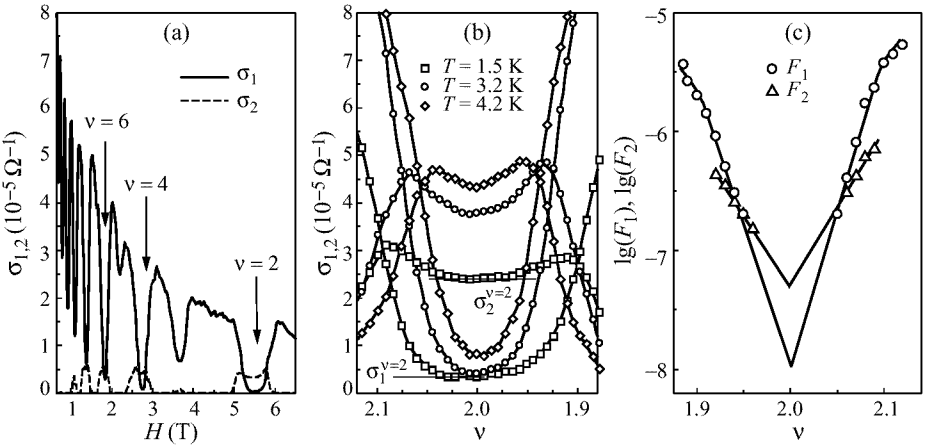

Fig. 1. (a) The experimental dependences of σ_1 and σ_2 on the magnetic field H, $T = 1.5$ K, $f = 30$ MHz; (b) Dependences of σ_1 and σ_2 on the filling factor near $\nu = 2$ at $T = 1.5$–4.2 K, $f = 30$ MHz; (c) The dependences of $\lg(F_1) = \lg(\sigma_1 - \sigma_1^{\nu=2})$ and $\lg(F_2) = \lg(\sigma_2 - \sigma_2^{\nu=2})$ vs ν near $\nu = 2$, $T = 1.5$ K.

$\nu = 2$ the relation $\sigma_2 > \sigma_1$ earlier predicted by Efros for the case of *relaxation* hf-hopping conductivity is really demonstrated experimentally.

In our case we also deal with the *relaxation*, or *phonon-assisted*, hf absorption due to phonon-assisted transitions which lead to a lag of the levels populations with respect to microwave-induced variation in the inter-level spacing. One can obtain

$$\sigma_1 = \pi^2 g^2 \xi^3 \omega e^4 \left(\mathcal{L}_T + \mathcal{L}_\omega/2\right)^2 / \left(2\varepsilon_s\right) . \tag{1}$$

Here g is (constant) single-electron density of states at the Fermi level, ξ is the localization length of the electron state, $\mathcal{L}_T = \ln J/kT$, J is a typical value of the energy overlap integral which is of the order of the Bohr energy, while $\mathcal{L}_\omega = \ln(\gamma_0/\omega)$; ε_s is the dielectric constant of GaAs. Eq. (1) is valid provided the logarithmic factors are large. Note that the product $r_\omega = \xi(\mathcal{L}_T + \mathcal{L}_\omega/2)$ is a distance between the sites forming a hopping pair. Note that (1) is similar to the one obtained in Ref. [1], however it differs by some logarithmic factors and numerical factor 1/4.

Analysis of $\sigma_2(\omega)$ is a bit more complicated because virtual zero-phonon transitions give a comparable contribution. The analysis gives the following ratio,

$$\frac{\sigma_2}{\sigma_1} = \frac{2\mathcal{L}_\omega\left(\mathcal{L}_T^2 + \mathcal{L}_T\mathcal{L}_\omega/2 + \mathcal{L}_\omega^2/12\right) + 4c\mathcal{L}_T^2\,\mathcal{L}_c}{\pi\left(\mathcal{L}_T^2 + \mathcal{L}_T\mathcal{L}_\omega + \mathcal{L}_\omega^2/4\right)}. \tag{2}$$

Here $\mathcal{L}_c = \ln(\hbar\omega_c/kT)$, ω_c is the cyclotron frequency, while $c \geq 1$ is a numerical factor depending on the density of states in the region between the Landau levels. Using the estimate for γ_0 from Ref. [5],

$$\gamma_0 = 4\pi e^2 K^2 kT/\varepsilon_s \hbar^2 V,$$

valid for the piezoelectric relaxation mechanism, as well as other parameters relevant to the present experiment, one concludes that in the hopping regime $\sigma_2 \geq \sigma_1$. This conclusion

agrees with the experimental results obtained for the middles of the Hall plateaus at 5.5 T and 2.7 T and make us sure that the conductance mechanism in these regions is hopping.

Given an experimental value of σ_1, one can obtain from Eq. (1) the localization length ξ provided the single-electron density of states, g, is known for for given values of magnetic field. This quantity has been obtained from the temperature dependence measurements of thermally-activated dc conductivity [6, 7]. It has been shown that for small even filling factors the density of states in the plateau regions is finite and almost field-independent.

Using the density of states versus mobility curve from Ref. [6] obtained for a sample similar to ours, we estimate the DOS as $g = 2.5 \times 10^{24}$ cm$^{-2}\cdot$erg^{-1}. On the other hand, according to Ref. [7], the DOS as a function of magnetic field H can be expressed by the interpolation formula

$$g(H) = g_0 / \left[1 + \sqrt{\mu H}\right], \tag{3}$$

where μ is the mobility of the 2D-electrons while $g_0 = m/(\pi\hbar^2)$ is the 2D DOS at $H = 0$. From Eq. (3) we obtain for $H = 5.5$ T the DOS $g = 1.7 \times 10^{24}$ cm$^{-2}\cdot$erg^{-1}.

Using the first estimate for the DOS one obtains $\xi = 6.5 \times 10^{-6}$ cm, that is about 1.6 times greater than the spacer thickness, $l_{sp} = 4 \times 10^{-6}$ cm. On the other hand, it is the spacer width, which characterizes the random potential correlation length in the 2DEG layer. Hence, this fact contradicts to our interpretation of the experimental results in terms of pure nearest-neighbor pair hopping.

To solve the controversy, we assume that the hf hopping conductivity of the 2DEG channel is shunted by the hopping along the doping Si δ-layer.

This assumption can be substantiated as follows. Let us suppose that in the middle of the Hall plateau σ_1 is entirely determined by the hopping conductivity along the Si δ-layer. Such a contribution is weakly dependent on magnetic field because the latter is too weak to deform substantially the wave functions of Si-dopants. Then the contribution to σ_1 associated with 2D layer is just a difference between the experimentally measured σ_1 in a given H and its value at $\nu = 2$.

Let us analyze dependences of the differences $F_1 \equiv \sigma_1 - \sigma_1^{\nu=2}$ and $F_2 \equiv \sigma_2 - \sigma_2^{\nu=2}$ on the filling factor ν. The plots of lg F_i versus ν are shown in Fig. 1(c). Both curves tend to straight lines, and in this way they can be extrapolated to $\nu = 2$. On the other hand, as it has been mentioned, at small even ν the shunting of 2DEG by Si δ-layers is important. Consequently, F_i are determined by the contributions of the 2D electron channel. Indeed, the Si-δ-layer's contributions to σ_1 and σ_2 at $\nu = 2$ are 4×10^{-7} Ω^{-1} and 2.4×10^{-6} Ω^{-1}, respectively. These quantities are more than order of magnitude larger than the quantities $F_1 = 10^{-8}$ Ω^{-1} and $F_2 = 5 \times 10^{-8}$ Ω^{-1} obtained by extrapolation of the experimental curves. Using the extrapolated values of F_1 and F_2 to extract the 2DEG contributions to σ_1 and σ_2, one can calculate the electron localization length at $\nu = 2$ from Eq. (1).

It should be noticed here that the experimental ratio $F_2/F_1 = 5$ is close to the theoretical value 4.2 coming from Eq. (2). The localization length at $\nu = 2$ obtained in this way is $\xi = 2 \times 10^{-6}$ cm, which is a half of the spacer width. This estimate makes realistic the "two-site model" which we have extensively used. Construction similar to that of Fig. 1(c) ($T = 1.5$ K) has been performed for all temperatures of the 1.5–4.2 K range. The temperature dependence analysis of σ_2 and σ_1 obtained as an extrapolation for $\nu = 2$ has shown that both components do not depend on T. This fact confirms the existence in this region of a hopping hf conductivity (see Eq. (2)). Both σ_1 and σ_2 begin to grow at $T > 3.2$ K. The idea that the 2D hf-conductivity of heterostructures in magnetic fields corresponding to small ν is shorted up by the hopping conductivity along the Si-δ-layers

could be confirmed by simple calculations of the localization length in the Si-δ-layers. Calculations with the use of Eq. (1) provide the value $\xi = 7 \times 10^{-7}$ cm, which is of the same order as the interatomic distance in a δ-layer. So one could use the same term "two-site model" when considering the hopping conductivity along the δ-layer. It should be emphasized, however, that from the above value of ξ in 2D channel the hopping length r_ω is estimated 1.4×10^{-5} cm. Consequently, there is an interplay between hops to the nearest and more remote neighbors. A more rigorous theory for this situation should be worked out. This theory should also explain why the dependences $\sigma_1(H)$ and $\sigma_2(H)$ in the vicinity of ν=2 appear different – the $\sigma_1(H)$-dependence is more pronounced than the $\sigma_2(H)$-one. According to the "two-site model", both dependences are determined by the $\xi(H)$ dependence and should be similar. Indeed, the ratio (2) is almost field-independent. It follows from the experiments that there exists an additional mechanism leading to the pronounced decrease of σ_2 as the Fermi level falls into the extended states. A probable mechanism is thermal activation of electrons from the Fermi level to the upper Landau band, leading to a decrease of the number of pairs responsible for the hopping conductivity, and to a screening of the electric field of SAW.

Acknowledgments

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